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Review

Augmented Reality and Virtual Reality in Thoracic Surgery: Current Applications and Objective Assessment of Surgical Competency —A Systematic Review

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Abstract

Background/Objectives: Augmented reality (AR) and virtual reality (VR) are increasingly utilized across the perioperative continuum in thoracic surgery. We performed a systematic review to elucidate the clinical utility of AR/VR technologies in general thoracic surgery, identify current technological trends, and evaluate their role as objective assessment tools for surgical competency. **Methods:** A comprehensive systematic search of the PubMed database was conducted from inception through 6 June 2026 in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Eligible peer-reviewed studies were categorized according to their clinical phase of utilization, perioperative surgical outcomes, and objective simulator-derived competency metrics. **Results:** A total of 1,013 records were initially identified, of which 74 met the inclusion criteria and were analyzed. Clinical applications of AR/VR in thoracic surgery spanned three principal domains: (1) surgical education and training, (2) preoperative anatomical planning and resection simulation, and (3) real-time intraoperative navigation (encompassing non-anatomical tumor localization and anatomical bronchovascular guidance). Integration of artificial intelligence (AI) further accelerated three-dimensional anatomical segmentation and intraoperative registration workflows. Across nine comparative cohort studies, AR/VR or three-dimensional guidance was associated with significantly shorter operative times in 77.8% (7/9) and lower estimated intraoperative blood loss in 55.6% (5/9) of studies without increasing postoperative complications. Furthermore, validated VR simulation platforms reliably stratified novice, intermediate, and experienced surgeons using automated kinematic metrics. **Conclusions:** AR and VR technologies enhance surgical training, complex segmentectomy planning, and intraoperative navigation. Standardized VR scoring systems incorporating procedural time, simulated blood loss, and instrument motion dynamics are warranted to advance objective surgical credentialing.

Keywords: augmented reality; virtual reality; mixed reality; extended reality; thoracic surgery; surgical simulation; intraoperative navigation; competency assessment; artificial intelligence

1. Introduction

Extended reality (XR)—an umbrella term encompassing virtual reality (VR), augmented reality (AR), and mixed reality (MR)—has rapidly transitioned from experimental prototypes into essential clinical instruments in modern surgical practice. Specifically, VR immerses the user in a completely simulated digital environment via a head-mounted display (HMD), AR superimposes digital information directly onto the user's real-world view (such as a surgical monitor or optical display),

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and MR anchors interactive three-dimensional (3D) virtual holograms into the physical environment, enabling real-time spatial manipulation. Thoracic surgeons increasingly employ these modalities throughout the perioperative pathway, including surgical education, patient-specific anatomical evaluation, preoperative procedural planning and simulation, intraoperative navigation, and postoperative care. Following landmark clinical trials such as JCOG0802/WJOG4607L and CALGB 140503, which established anatomical segmentectomy as a standard of care for small-sized peripheral non-small cell lung cancer (NSCLC) [1,2], the need for precise evaluation of patient-specific bronchovascular anatomy, intersegmental plane demarcation, and adequate resection margins has risen substantially. Whereas conventional two-dimensional (2D) computed tomography (CT) requires surgeons to mentally reconstruct planar cross-sectional slices into a 3D anatomical map, 3D reconstruction and AR/VR platforms provide an intuitive spatial representation of anatomy that facilitates preoperative planning and intraoperative orientation [3–7]. However, widespread clinical adoption requires familiarity with specialized hardware interfaces (such as HMDs or gesture-control sensors) and entails higher implementation costs compared with standard 2D CT imaging. Moreover, with the rapid expansion of robot-assisted thoracic surgery (RATS) and uniportal (single-port) video-assisted thoracoscopic surgery (VATS), where direct manual palpation is absent or limited, surgeons rely heavily on enhanced visual guidance. This systematic review aims to comprehensively assess the clinical utility and technological evolution of AR/VR in thoracic surgery, summarize comparative perioperative outcomes, and explore the emergence of VR-based objective metrics for surgical competency.

2. Materials and Methods

2.1. Search Strategy and Eligibility Criteria

We conducted a systematic literature search of the PubMed database from database inception through 6 June 2026 (with no restriction on the earliest publication year), conforming to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Supplementary Table S1). This review protocol was not prospectively registered in PROSPERO. The electronic search was executed using the following Boolean keyword combinations: “Augmented Reality Thoracic Surgery”, “Augmented Reality Lung Cancer” (as well as “Augment Reality Thoracic Surgery” and “Augment Reality Lung Cancer”), “Virtual Reality Thoracic Surgery”, “Virtual Reality Lung Cancer”, “Mixed Reality Thoracic Surgery”, or “Mixed Reality Lung Cancer”. Inclusion criteria encompassed peer-reviewed original articles and review articles focusing on the application of AR, VR, or MR in general thoracic surgery—including surgical education, preoperative planning, intraoperative navigation, and objective surgical skill assessment. Although pairing “Thoracic Surgery” queries with “Lung Cancer” queries yielded a primary emphasis on pulmonary resections, non-pulmonary general thoracic procedures (such as chest wall or mediastinal tumor resections) captured by the broad thoracic surgery terms were also eligible. The exclusion criteria were: (1) single case reports or case series with fewer than three patients; (2) non-English language publications; (3) non-peer-reviewed commentaries, editorials, letters to the editor, errata, and conference abstracts; and (4) studies unrelated to general thoracic surgery (such as cardiac surgery, vascular intervention, orthopedic surgery, or isolated diagnostic bronchoscopy without surgical resection) or lacking AR/VR/MR technology. Reference lists of relevant review articles were manually cross-referenced to identify additional eligible studies.

2.2. Data Extraction and Synthesis

Retrieved records were independently reviewed and categorized according to the phase of clinical utilization: (1) education and surgical training, (2) preoperative planning and simulation, and (3) intraoperative navigation. For comparative studies evaluating perioperative outcomes, data regarding study design (single- vs. multi-center, randomization, or propensity score matching [PSM]), sample size, surgical approach (multi-port VATS, uniportal VATS, or RATS), experimental

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technological platform, operative time, estimated intraoperative blood loss, postoperative complications, length of hospital stay, and duration of chest tube drainage were systematically extracted. Furthermore, studies evaluating objective skill assessment via VR simulators were analyzed with respect to quantitative performance metrics and construct validity.

3. Results

3.1. Literature Search and PRISMA Flow

The initial multi-keyword search identified 1,013 records: "Augmented Reality Thoracic Surgery" (N = 189), "Augmented Reality Lung Cancer" (N = 51), "Virtual Reality Thoracic Surgery" (N = 401), "Virtual Reality Lung Cancer" (N = 105), "Mixed Reality Thoracic Surgery" (N = 200), and "Mixed Reality Lung Cancer" (N = 67) (Figure 1). After removing duplicate publications (N = 439), title and publication-type screening of the remaining 574 records excluded 40 records, comprising non-English publications (N = 26), commentaries (N = 6), editorials (N = 5), errata (N = 2), and a letter to the editor (N = 1). During the subsequent abstract screening of 534 articles, 389 studies outside general thoracic surgery—including diagnostic bronchoscopy (N = 46), cardiovascular surgery and vascular intervention (N = 118), non-surgical cardiovascular disease (N = 30), orthopedic surgery (N = 51), and other unrelated disciplines (N = 144)—were excluded. Following full-text eligibility assessment of the remaining 145 articles (107 original studies and 38 review articles), the 38 review articles and 38 original studies with inadequate outcome reporting were excluded, while 5 additional original studies were identified via manual bibliography screening. Ultimately, 74 original studies were included in this systematic review (Figure 1). The overall clinical workflow and primary applications of AR/VR technology across the perioperative pathway are illustrated in the Graphical Abstract.

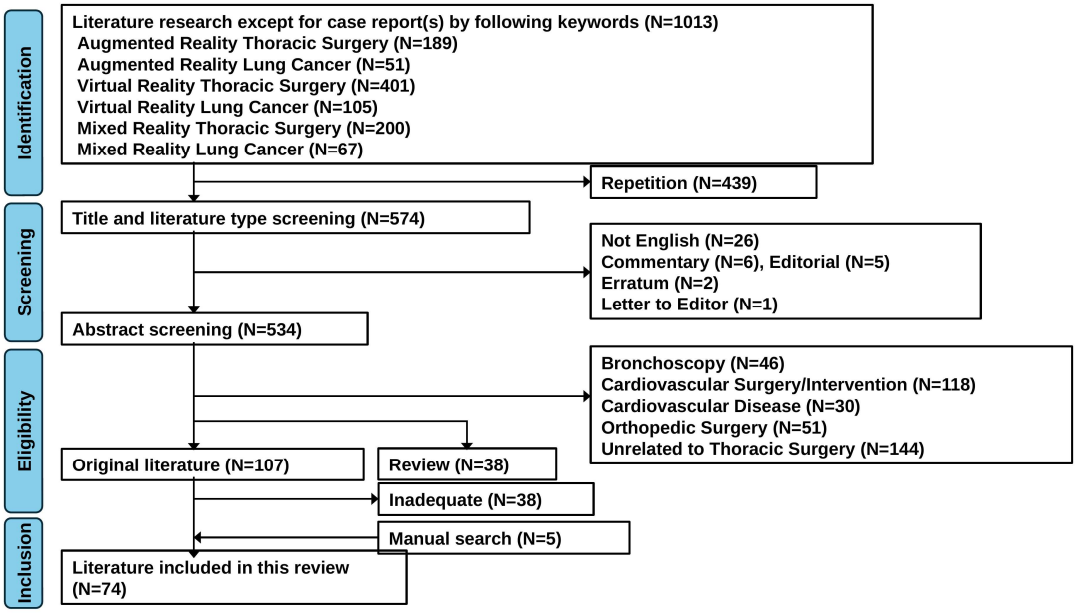

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram detailing the literature identification, screening, eligibility assessment, and inclusion process.

3.2. Education and Surgical Training

AR and VR technologies have transformed surgical education for medical students and thoracic surgery trainees. Compared with conventional teaching reliant on textbooks or planar 2D radiological images, immersive VR environments provide superior visualization of 3D anatomical

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spatial relationships to facilitate trainee comprehension and retention. While physical bench models also allow trainees to practice procedures without patient risk, VR cognitive and technical simulators offer distinct advantages over static bench models by providing automated performance feedback, diverse patient-specific anatomical variations or pathology, and unlimited procedural repetition without recurring consumable material costs [8]. Furthermore, within a simulation training environment, 3D video visualization systems have proven superior to 2D displays in accelerating skill acquisition for uniportal VATS [9].

Nevertheless, several studies emphasized that synthetic 'dry' physical bench models and high-fidelity 'wet' animal tissue models retain specific tactile advantages over pure VR platforms [10,11]. In a prospective randomized trial, von Bechtolsheim et al. demonstrated that while VR training provides sufficient fundamental competence, training on real robotic hardware was superior for developing delicate tissue-handling skills [12]. Similarly, in a comprehensive review of VATS simulators (synthetic dry models, wet animal tissue models, and AR/VR simulators), Grossi et al. concluded that although digital simulators significantly enhance surgical training curricula, hybrid approaches combining VR with physical models remain optimal and no simulation modality can entirely replace supervised clinical experience [13].

3.3. Preoperative Planning and Resection Simulation

Accurate recognition of individual pulmonary vascular and bronchial branches is essential to prevent intraoperative catastrophic bleeding and to achieve complete oncologic resection. With the increasing adoption of anatomical segmentectomy for early-stage lung cancers, preoperatively mapping intersegmental planes and confirming adequate surgical margins from the target nodule are of increasing clinical value.

Multiple studies have established that patient-specific 3D reconstructions and immersive AR/VR platforms provide detailed visualization of pulmonary bronchovascular anatomy, enabling precise operative planning prior to skin incision [3–5]. In a series of 50 consecutive segmentectomies, Bakhuis et al. reported that preoperative VR planning led to essential modifications of the surgical plan—such as altered segmental target selection or vascular division strategy—in a substantial proportion of cases [5]. Petrella et al. further highlighted that holographic AR visualization was particularly advantageous for identifying aberrant vascular branching in upper lobectomies [6]. Reflecting these capabilities, an international Delphi consensus report by 21 thoracic surgery experts strongly recommended preoperative 3D bronchovascular reconstruction prior to undertaking complex segmentectomies and minimally invasive pulmonary resections [7].

3.4. Intraoperative Navigation: Non-Anatomical vs. Anatomical Guidance

Intraoperative AR/VR utilization bifurcates into two distinct domains: non-anatomical tumor localization and anatomical structure guidance.

Non-Anatomical Tumor Localization: Precise intraoperative localization of small, sub-centimeter, non-palpable ground-glass opacity (GGO) nodules is critical during sublobar resection to avoid unexpected margin compromise or unplanned conversion to lobectomy. Conventional localization techniques (such as CT-guided percutaneous hook-wire placement, microcoils, and transbronchial dye marking) entail procedural discomfort, ionizing radiation exposure, scheduling delays between the CT suite and operating room, and potential complications including pneumothorax, pulmonary hemorrhage, wire dislodgement, and air embolism. XR and AR overlay systems address these limitations by projecting 3D virtual nodule locations onto the surgical view or patient thorax to guide non-invasive or minimally invasive localization. Specifically, Feng et al. integrated preoperative 3D virtual modeling with temporary clamping of the target segmental vessel and a modified pure-oxygen inflation–deflation technique to match the virtual segment with the inflated lung on the thoracoscopic monitor, successfully localizing 53 non-palpable nodules (median diameter 9.0 mm) without percutaneous puncturing [14]. Izawa et al. developed a non-invasive XR-aided marking method that projects 3D virtual anatomical models onto the thoracoscopic surgical

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field during sublobar resection, eliminating the risk of physical marker dislodgement [15]. Furthermore, in a prospective non-inferiority randomized clinical trial, Qi et al. compared head-mounted MR holographic guidance (using an HMD anchored to surface fiducial markers) against conventional CT-guided hook-wire localization prior to VATS, demonstrating non-inferior localization accuracy (mean deviation difference −1.34 mm), significantly shorter procedural localization time, and reduced complication rates [16].

Anatomical Guidance: Anatomical AR navigation superimposes 3D patient-specific vascular and bronchial meshes directly onto the live thoracoscopic monitor or robotic console display. Peek et al. developed a semi-automated 3D registration workflow utilizing stereo camera calibration and a scale-adaptive iterative closest point (ICP) algorithm to transform the intraoperative surgical field into a 3D point-cloud surface, accurately registering preoperative 3D vascular models onto live VATS and RATS video feeds within 5 minutes (median registration error 0.20 mm) [17]. In addition, Zheng et al. evaluated a streaming HMD-based VR digital-twin platform (OpVerse) against a conventional desktop 3D workstation (Synapse 3D) across 13 complex thoracic procedures, demonstrating significantly higher System Usability Scale scores (73.3 ± 14.6 vs. 53.8 ± 11.6, $p = 0.0006$), superior perceived ease of use, and enhanced 3D anatomical comprehension through interactive model rotation and adjustable tissue transparency [18].

3.5. Impact of AR/VR on Perioperative Surgical Outcomes

Nine comparative studies directly evaluated perioperative clinical outcomes between AR/VR or 3D-guided thoracic surgery and conventional non-AR/VR approaches (Table 1 and Figure 2) [19–27].

Operative time: Of the nine studies, 77.8% (7/9) demonstrated a statistically significant reduction in total operative time in the AR/VR or 3D-assisted cohort compared with conventional controls [19–21,23,24,26,27]. Conversely, one study (Wu et al. [25]) reported longer operative times in the real-time 3D navigation cohort—which was attributed to the additional intraoperative time required to set up and reference the 3D navigation system as well as a higher proportion of complex subsegmental dissections—while one study (Xu et al. [22]) observed no significant difference.

Intraoperative blood loss: Five of the nine comparative studies (55.6%) reported statistically significant reductions in estimated intraoperative blood loss with AR/VR or 3D-assisted guidance [20,21,23,24,26], while the remaining studies reported no significant difference [19,22,25,27]. Across studies reporting a statistically significant difference, the absolute reduction in mean estimated blood loss was generally modest (typically ranging from 10 to 50 mL between cohorts), and these findings must be interpreted in light of the inherent subjectivity of intraoperative blood loss estimation and the inability to blind operating surgeons to the navigation intervention.

Postoperative complications, length of hospital stay, and chest tube duration: Overall postoperative complication rates showed no significant difference between experimental and control cohorts in 77.8% (7/9) of the studies [19,21–26] (although Wu et al. [25] noted a higher transient postoperative day 1 air leak rate in the precision segmentectomy group despite equivalent overall complications, She et al. [20] reported lower individual rates of air leak and hemoptysis alongside equivalent rates of pneumonia, arrhythmia, and atelectasis, and Liu et al. [27] did not assess overall postoperative complications). Regarding chest tube duration, 55.6% (5/9) of the studies reported no significant difference between cohorts [21,22,25–27], one study (11.1%; She et al. [20]) demonstrated a significantly shorter chest tube duration in favor of the 3D-assisted cohort, and three studies (33.3%) did not assess this endpoint [19,23,24]. For length of hospital stay, one study (11.1%; Li et al. [24]) reported a significantly shorter postoperative hospital stay in the AR and 3D-printing cohort, five studies (55.6%) reported no significant difference [19–21,26,27], and three studies (33.3%) did not evaluate hospital stay [22,23,25]. Collectively, these findings confirm that AR/VR guidance improves operative efficiency without compromising patient safety.

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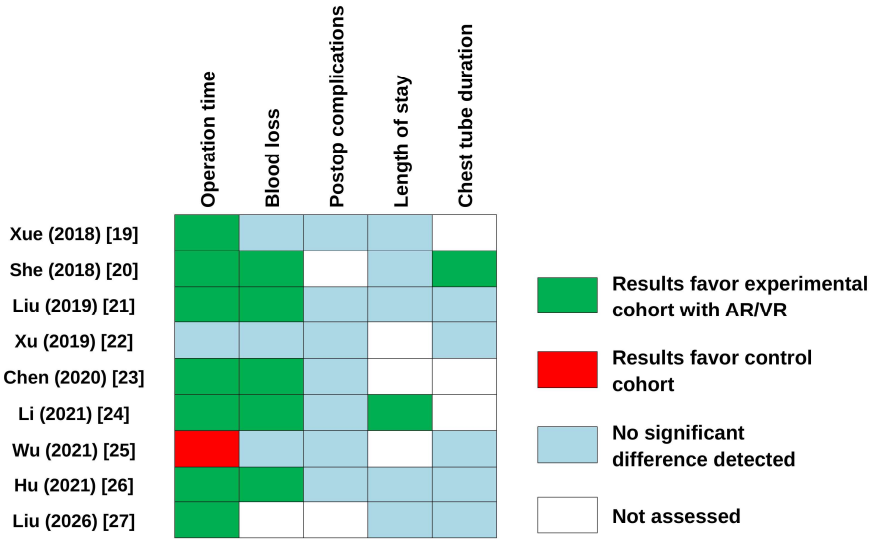

Figure 2. Heatmap illustrating comparative perioperative outcomes (operation time, intraoperative blood loss, postoperative complications, length of hospital stay, and chest tube duration) between augmented reality (AR)/virtual reality (VR) or three-dimensional (3D)-assisted cohorts and conventional cohorts across the nine comparative studies [19–27].

Table 1. Summary of comparative studies evaluating perioperative outcomes of augmented reality (AR), virtual reality (VR), and three-dimensional (3D) guidance in thoracoscopic pulmonary segmentectomy.

Study [Ref]	Study Design	Sample Size (Exp vs. Ctrl)	Surgical Approach	3D / AR / VR Platform	Outcomes Favoring AR/VR	Outcomes Favoring Ctrl	No Significant Difference
Xue (2018) [19]	Retrospective, single-center	cStage IA1 GGO (N = 36 vs. 32)	Multi-port VATS	3D-CT model simulation	Operative time, surgical margin distance	None	Blood loss, postop. morbidity, length of stay
She (2018) [20]	Retrospective, single-center	NSCLC (N = 51 vs. 51)	Multi-port VATS	3D-CTBA + 3D-VATS (stereoscopic monitor)	Operative time, blood loss, chest tube duration, drainage volume, air leak, hemoptysis	None	Pneumonia, arrhythmia, atelectasis, length of stay, cost
Liu (2019) [21]	Retrospective, single-center	NSCLC or metastasis (N = 53 vs. 39)	Multi-port VATS	3D-CT model or 3D printing	Operative time, blood loss	None	Postop. morbidity, length of stay, chest tube duration

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Study [Ref]	Study Design	Sample Size (Exp vs. Ctrl)	Surgical Approach	3D / AR / VR Platform	Outcomes Favoring AR/VR	Outcomes Favoring Ctrl	No Significant Difference
Xu (2019) [22]	Retrospective, single-center	Pulmonary nodule(s) (N = 96 vs. 37)	Uniportal VATS	IQQA-3D imaging software	None	None	Operative time, blood loss, postop. morbidity, chest tube duration
Chen (2020) [23]	Quasi-RCT, single-center	Pulmonary GGO(s) (N = 51 vs. 38)	Uniportal VATS	3D printing from 3D-CT model	Operative time, blood loss, conversion rate	None	Postop. morbidity
Li (2021) [24]	Retrospective, single-center, PSM	Early NSCLC with GGO (N = 55 vs. 87; 54 vs. 54 PSM)	Multi-port VATS (seg. or subseg.)	3D printing + head-mounted AR display	Operative time, blood loss, length of stay, usability score	None	Postop. morbidity, procedural success rate
Wu (2021) [25]	Retrospective, single-center, PSM	Pulmonary GGO(s) (N = 55 vs. 298; 55 vs. 55 PSM)	Uniportal VATS	Real-time 3D navigation guidance	Dissected lymph nodes, surgical margin adequacy	Operative time, POD 1 air leak rate	Blood loss, overall postop. morbidity, chest tube duration
Hu (2021) [26]	Retrospective, single-center	Stage IA NSCLC (N = 30 vs. 35)	Multi-port VATS	3D-CTBA + 3D printing	Operative time, blood loss	None	Postop. morbidity, length of stay, chest tube duration
Liu (2026) [27]	Prospective RCT, single-center	Early-stage NSCLC (N = 29 vs. 29)	Multi-port VATS	Contactless gesture 3D system (Ultraleap 3Di)	Operative time, image retrieval time	None	Blood loss, chest tube duration, R0 rate (100% both)

Abbreviations: 3D, three-dimensional; 3D-VATS, three-dimensional video-assisted thoracoscopic surgery using a stereoscopic monitor; AR, augmented reality; CT, computed tomography; CTBA, computed tomography bronchography and angiography; Ctrl, control cohort; Exp, experimental cohort; GGO, ground-glass opacity; IQQA, Intelligent Qualitative and Quantitative Analysis (EDDA Technology); NSCLC, non-small cell lung cancer; POD, postoperative day; postop., postoperative; PSM, propensity score matching; RCT, randomized controlled trial; seg., segmentectomy; subseg., subsegmentectomy; VATS, video-assisted thoracoscopic surgery; VR, virtual reality.

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3.6. Objective Competency Assessment and Skill Quantification

In addition to clinical planning and intraoperative assistance, VR systems provide a standardized framework for objectively assessing surgical competency. Three key studies established construct validity by stratifying thoracic surgeons into distinct experience tiers (novice, intermediate, and experienced surgeons) using VR simulation metrics (Table 2 and Figure 3) [28–30].

Jensen et al. [28] and Haidari et al. [30] validated the Video-Assisted Thoracoscopic Surgery Assessment Tool (VATSAT) within a VR lobectomy simulator, demonstrating that structured virtual assessment can reliably determine whether a trainee has achieved technical competence prior to performing supervised clinical resections.

Haidari et al. [29] further demonstrated that automated, simulator-derived kinematic and performance metrics—specifically total procedural time, simulated intraoperative blood loss within the virtual environment, total instrument path length, instrument angular motion dynamics, and mechanical traction or parenchymal injury to the bronchus and lung lobe—distinguished novice, intermediate, and experienced surgeons with high statistical fidelity.

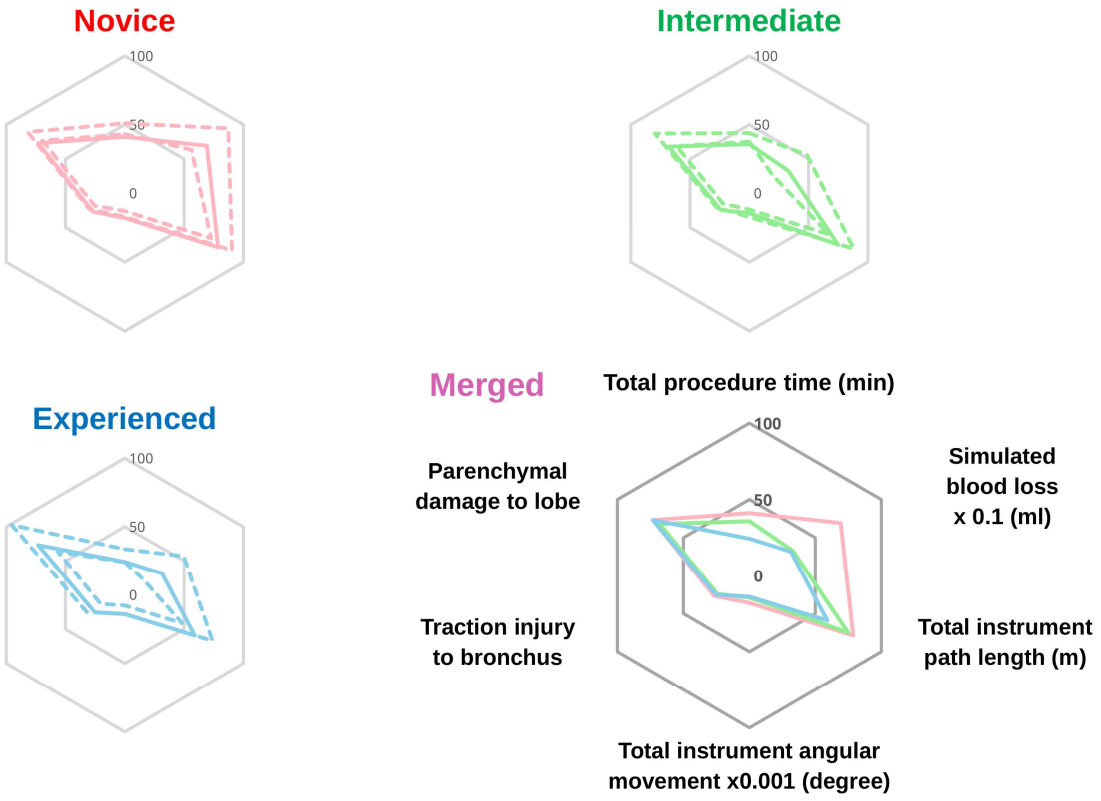

Figure 3. Radar charts illustrating objective kinematic and technical performance metrics (total procedure time, simulated blood loss, total instrument path length, total instrument angular movement, traction injury to bronchus, and parenchymal damage to lobe) stratified by surgeon experience level (Novice, Intermediate, Experienced, and Merged) in a virtual reality (VR) lobectomy simulation environment (figure adapted from data reported by Haidari et al. (2022) [29]).

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Table 2. Quantitative and qualitative performance metrics utilized for virtual reality (VR)-based surgical competency assessment.

Study [Ref]	Simulator System	Assessment Method	Evaluated Variables
Jensen (2019) [28]	VR VATS Lobectomy	VATSAT scoring criteria	Dissection of hilum, pulmonary vein, pulmonary artery, and bronchus; respect for tissue; general technical skill
Haidari (2022a) [29]	VR VATS Lobectomy (5 lobes)	Automated quantitative tracking	Total procedure time, simulated intraoperative blood loss, instrument path length, instrument angular motion, tissue traction/parenchymal damage to bronchus and lung lobe
Haidari (2022b) [30]	VR VATS Lobectomy	VATSAT pass/fail benchmarking	Targeted anatomical dissection, structural identification, tissue-handling safety

Abbreviations: VATS, video-assisted thoracoscopic surgery; VATSAT, Video-Assisted Thoracoscopic Surgery Assessment Tool; VR, virtual reality.

3.7. Artificial Intelligence Synergy in AR/VR Workflows

Artificial intelligence (AI) has rapidly converged with AR/VR systems to enhance 3D model segmentation accuracy and workflow efficiency [31,32]. Convolutional neural networks and deep-learning algorithms enable automated anatomical segmentation of CT data, automated labeling of bronchovascular variants, and rapid 3D model generation, substantially reducing manual reconstruction time.

Sadeghi et al. reported the successful integration of AI-driven digital anatomical labeling into immersive 3D VR planning for complex segmentectomy [33]. The same research group subsequently accomplished real-time intraoperative fusion of AI-annotated AR overlays directly within the robotic console display during RATS pulmonary resection [34]. Beyond anatomical segmentation, AI models integrated with perioperative clinical data have shown potential for predicting postoperative air leaks, cardiopulmonary complications, and clinical deterioration [31,32].

4. Discussion

Thoracic surgical oncology is experiencing two concurrent shifts: the establishment of anatomical segmentectomy as an oncologically sound standard of care for small, peripheral early-stage NSCLC [1,2], and the widespread adoption of advanced minimally invasive platforms, notably RATS and uniportal (single-port) VATS [35–37]. Integrating AR and VR technologies into these workflows directly addresses the heightened anatomical and technical demands of modern sublobar and minimally invasive resections.

Our systematic review demonstrates that AR/VR technologies confer clinical value across three sequential phases mirroring the perioperative workflow: preclinical education, preoperative planning, and intraoperative navigation. First, in surgical training, VR simulators complement physical dry and wet bench models by offering unlimited, risk-free procedural repetition alongside automated kinematic feedback [8–13]. Second, in preoperative planning for anatomical segmentectomy, defining the target intersegmental plane and securing tumor-free surgical margins of ≥2 cm (or at least the maximum tumor diameter) are paramount. Patient-specific 3D reconstructions and immersive VR platforms allow preoperative simulation of stapler division planes, instrument angulation, and target bronchovascular dissection pathways, enabling early identification of aberrant vascular branches and reducing the risk of inadvertent vascular injury or ischemia of adjacent segments [3–7]. Third, during intraoperative navigation, XR and AR systems support both non-anatomical tumor localization and anatomical structure guidance. For small, non-

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palpable GGO lesions, AR/MR projections provide a non-invasive, radiation-free alternative to percutaneous hook-wire or transbronchial dye marking, avoiding marker dislodgement and puncture-related pneumothorax or hemorrhage [14–16,38]. Concurrently, deformable and point-cloud AR registration algorithms are advancing the real-time superimposition of 3D bronchovascular meshes onto the live thoracoscopic or robotic view [17,18,34]. Furthermore, while the majority of studies in this review focused on pulmonary resections for lung cancer, AR/VR applications in general thoracic surgery are actively expanding to chest wall tumor resection, posterior mediastinal neurogenic tumor excision, infraclavicular first-rib resection for thoracic outlet syndrome, and surgical planning for pediatric congenital thoracic malformations [39–43].

The clinical utility of AR/VR is particularly pronounced in RATS and uniportal VATS. Although next-generation robotic platforms (such as the da Vinci 5) have begun incorporating force-sensing haptic feedback, the vast majority of currently deployed robotic systems lack direct tactile sensation, requiring surgeons to rely on visual cues to gauge tissue tension and locate subsurface structures. Superimposing patient-specific 3D anatomical models directly into the robotic console stereoscopic viewer (e.g., via TilePro® or AI-assisted AR fusion) helps bridge this sensory gap by alerting the surgeon to critical pulmonary artery or vein branches prior to dissection [3,4,34]. Similarly, in uniportal VATS, where instrument angulation and viewing angles are restricted to a single intercostal incision, 3D and AR/VR guidance facilitates spatial orientation [22,23,27]. While 77.8% of reviewed comparative studies demonstrated statistically significant reductions in operative time and 55.6% reported lower estimated blood loss with 3D or AR/VR assistance [19–21,23,24,26,27], the absolute reductions in estimated blood loss were modest (typically 10–50 mL) and should be interpreted cautiously given the inaccuracy of visual blood loss estimation and the lack of surgeon blinding.

Equally important is the emerging role of VR simulation in objective surgical credentialing. Traditional surgical training has relied on subjective visual appraisal by senior proctors (e.g., global rating scales), which is susceptible to inter-rater variability. As demonstrated in Table 2 and Figure 3, validated VR simulation platforms capture objective kinematic parameters—including procedural time, simulated intraoperative blood loss, instrument path length, angular motion economy, and mechanical traction stress on the bronchus and lung parenchyma [28–30]. These quantitative metrics reliably discriminate experienced surgeons from novices and intermediates, offering a reproducible foundation for competency-based credentialing and shortening the learning curve for complex pulmonary resections.

Several limitations of this systematic review must be acknowledged. First, our literature search was restricted to PubMed and English-language publications, which may have introduced database and language selection bias. Second, the included studies exhibited substantial heterogeneity across hardware platforms (HMDs, holographic displays, contactless gesture sensors, and 3D-printed models), surgical approaches (multi-port VATS, uniportal VATS, and RATS), and outcome definitions, precluding a formal quantitative meta-analysis. Third, most comparative studies were single-center retrospective analyses without surgeon blinding, making endpoints such as operative time and estimated blood loss susceptible to performance and measurement bias. Finally, as deformable AR registration and AI segmentation algorithms continue to evolve rapidly, multicenter prospective randomized trials are needed to validate their impact on clinical and oncological outcomes.

5. Conclusions

AR and VR technologies have matured into valuable clinical assets in thoracic surgery, delivering tangible benefits across surgical training, preoperative anatomical planning, and intraoperative navigation. In comparative clinical studies, 3D and AR/VR guidance is associated with reduced operative time and modest reductions in estimated intraoperative blood loss without compromising patient safety. Future efforts should prioritize integrating AI-driven automated segmentation with real-time deformable AR registration for lung deflation, alongside adopting

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standardized VR kinematic scoring systems to objectively evaluate and credential surgical competency.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org. Table S1: PRISMA 2020 Checklist.

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Abbreviations

The following abbreviations are used in this manuscript:

2D	Two-dimensional
3D	Three-dimensional
3D-VATS	Three-dimensional video-assisted thoracoscopic surgery
AI	Artificial intelligence
AR	Augmented reality
CT	Computed tomography
CTBA	Computed tomography bronchography and angiography
CTM	Congenital thoracic malformation
GGO	Ground-glass opacity
HMD	Head-mounted display
ICP	Iterative closest point
IQQA	Intelligent Qualitative and Quantitative Analysis
MR	Mixed reality
NSCLC	Non-small cell lung cancer
POD	Postoperative day
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSM	Propensity score matching
RATS	Robot-assisted thoracic surgery
RCT	Randomized controlled trial
VATS	Video-assisted thoracoscopic surgery
VATSAT	Video-Assisted Thoracoscopic Surgery Assessment Tool
VR	Virtual reality
XR	Extended reality

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